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14. ABSTRACT

Over the three years of this project, we obtained a substantial collection of results that relate the topology of the underlying communications network to the stability of the overall system, under the assumption of identical linear dynamics for each vehicle (nodes). These results characterize the stability of the system in terms of the frequency response of the individual evhicle dynamics and the eigenvalues of the Laplacian Matrix associated with the communications topology. Extensions to the basic stability theorem have been obtained that account for nonlinear plant dynamis, switching communications graphs, and disturbance propogation.

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INFORMATION FLOW IN COOPERATIVE CONTROL OF MULTI-VEHICLE SYSTEMS

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Final Report

AFOSR GRANT F49620-01-1-0460

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Abstract

This project focused on developing the underlying theory required to achieve integration of information flow into control analysis and design for cooperative tasks of multi-vehicle systems. By making use of tools from control theory, dynamical systems, and graph theory, we developed a framework for analyzing the effects of information and sensor topology on feedback systems and developing tools for designing information flow and control algorithms that build on this framework. We applied these ideas to several test problems involving real-time, distributed control of a set of multiple vehicles performing cooperative tasks. In addition to computational exploration through simulation, we implemented our algorithms on a multi-vehicle, wireless testbed for networked control, communications, and computing that was developed at Caltech.

1 Accomplishments

Over the three years of this project, we obtained a substantial collection of results that relate the topology of the underlying communications network to the stability of the overall system, under the assumption of identical linear dynamics for each vehicle (nodes). These results characterize the stability of the system in terms of the frequency response of the individual vehicle dynamics and the eigenvalues of the Laplacian matrix associated with the communications topology. Extensions to the basic stability theorem have been obtained that account for nonlinear plant dynamics, switching communication graphs, and disturbance propogation.

Graph Laplacians and Formation Stability

Our initial work used tools from graph theory and control theory to derive a simple stability criteria for formation stabilization [4]. The interconnection between vehicles (i.e., which vehicles are sensed by other vehicles) is modeled as a graph, and the eigenvalues of the Laplacian matrix of the graph are used in stating a Nyquist-like stability criterion for vehicle formations. The location of the Laplacian eigenvalues

[1]Now at Northrop Grumman

can be correlated to the graph structure, and therefore used to identify desirable and undesirable formation interconnection topologies. Building on this work, we have considered several problems that arise in cooperative control of multi-vehicle systems.

Vehicles in formation often lack global information regarding the state of all the vehicles, a deficiency which can lead to instability and poor performance. We have demonstrated how exchange of minimal amounts of information between vehicles can be designed to realize a dynamical system which supplies each vehicle with a shared reference trajectory [4]. When the information flow law is placed in the control loop, a separation principle is proven which guarantees stability of the formation and convergence of the information flow law regardless of the information flow topology.

Together, these results provide a framework for analyzing the stability of interconnected systems and understanding the relationship between the individual vehicle dynamics and the topology of the communications network through which the vehicles share information. Recent work has been aimed at extending these results to nonlinear systems, analyzing disturbance rejection properties (so-called string stability) using graph Laplacians, and studying the effects of switching communications topologies on stability.

Uncertain Communications Channels

Our work on graph Laplacians considered only the topology of the network connecting vehicles. In more realistic situations, one would like to have a more accurate model of the communications channel and understand the effects of the channel dynamics on the system performance. We explored this path by studying techniques for jump Markov processes, in which each Markov state corresponds to a given channel configuration. This framework can be used to model channels with varying delay, bandwidth, or SNR properties through a discrete collection of models.

Prior work in this area had shown that if the Markov state was known, it was possible to stabilize the jump Markov system under certain conditions. These conditions related to individual Markov state dynamics to the transition rates between the Markov states. We extended these results to allow the Markov state to be estimated (using, for example, the Viterbi algorithm) [7]. These results allow us to design control laws for the different communication channel conditions and interconnect them to achieve stability in the presence of uncertain channel conditions. We have applied the results to the specific case of changing network communications topology [6] and further extended the results to compute optimal control laws under fixed communications structure [5].

Nonlinear Networked Sytems

Further extension of the initial results in this grant considered stability analysis problem for nonlinear systems which have general linear feedback interconnections [3]. We presented necessary conditions for stability of a classification of interconnected

systems, and we gave some examples to provide insight into this problem. These conditions are related to positive definiteness of matrices associated with the feedback interconnection, and specialize to the common case where the Laplacian matrix of a graph represents the communication topology of the system.

Multi-Vehicle Wireless Testbed

The techniques developed under this grant have being implemented on the Caltech multi-vehicle testbed. The testbed consists of 8 mobile vehicles with embedded computing and communications capability. A unique feature of the testbed is the use of vehicles that have second order dynamics, requiring real-time feedback algorithms to stabilize the system while performing cooperative tasks.

Students supported by this project have been involved in implementing control laws for the testbed as well as developing the Bluetooth communications capability [1, 2]. This infrastructure was used to demonstrate theoretical results for control of interconnected systems [?].

2 Personnel Supported

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Postdoctoral scholars
Kristi Morgansen, Caltech (now at U. Washington)

Graduate students
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Laure Sinegre, Ecole des Mines (visitor)
David van Gogh, Caltech

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